

UNITED STATES UTILITY PATENT APPLICATION

HIGH-CURRENT AVALANCHE-TUNNELING AND INJECTION-
TUNNELING SEMICONDUCTOR-DIELECTRIC-METAL STABLE
COLD EMITTER, WHICH EMULATES THE NEGATIVE ELECTRON
AFFINITY MECHANISM OF EMISSION

INVENTORS:

Viatcheslav V. Ossipov
calle Fernández de los Rios 51, 1d
28015 Madrid, Spain

Alexandre M. Bratkovski
127 Laurel Way
Mountain View, CA 94040

Henryk Birecki
3001 Ross Rd.
Palo Alto, CA 94303

HIGH-CURRENT AVALANCHE-TUNNELING AND INJECTION-TUNNELING
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RELATED APPLICATIONS

The following application of the common assignee, which is hereby incorporated by reference in its entirety, may contain some common disclosure and may relate to the present invention:

- 5 U.S. Patent Application Serial No. __/__,__, entitled INJECTION COLD
EMITTER WITH NEGATIVE ELECTRON AFFINITY BASED ON WIDE-GAP
SEMICONDUCTOR STRUCTURE WITH CONTROLLING BASE (Attorney Docket
No. 10007287-1).

10 FIELD OF THE INVENTION

This invention relates generally to electron emitters. In particular, the invention relates generally to cold electron emitters of p-n cathode type.

BACKGROUND OF THE INVENTION

- 15 Electron emission technology exists in many forms today. Hot cathode ray tubes (CRT), where electrons are produced as a result of thermal emission from hot cathode heated by electrical current, are prevalent in many displays such as televisions (TV) and computer monitors. Electron emission also plays a critical role in devices such as x-ray machines and electron microscopes. Miniature cold cathodes may be used for integrated
20 circuits and flat display units. In addition, high-current density emitted electrons may be used to sputter or melt some materials.

In general, two types of electron emitters exist – “hot” and “cold” cathode emitters. The “hot” cathodes are based on thermal electron emission from surface heated

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by electric current. The cold cathodes can be subdivided into two different types: type A and B. The emitters of type A are based on the field emission effect (field-emission cathodes). The emitters of type B are the p-n cathodes using the emission of non-equilibrium electrons generated by injection or avalanche electrical breakdown processes.

5 Both types of emitters have drawbacks, which make them virtually impractical. For type A emitters (field emission type), one of the main drawbacks is the very short lifetime of such emitters. For example, the type A emitters may be operational for just hours, and perhaps even as short as minutes. In the cold field-emission cathodes (type A), electrons are extracted from the surface of a metal electrode by a strong electric field in
10 vacuum. The field cathodes have a short lifetime at large emitted currents, which are needed in recording devices and other applications.

With reference to Fig. 1A, operation of type A emitters will be described. Fig. 1A illustrates a typical energy diagram for a metallic surface illustrating a concept of a work function of a metal. As shown, a material, in this instance a metal, is on the left and a
15 vacuum region is on the right. E_F represents a Fermi level of the metal. The work function of the metal Φ_M is the energy required to move a single electron from the Fermi level in the metal into vacuum. Thus, the work function Φ_M is the difference between Vac and E_F . The work function Φ_M for metal is typically between 4 – 5 electron volts (eV).

20 In very strong external field the energy diagram changes, and behaves as a triangular potential barrier for the electrons (Fig. 1A, dashed line). When the external field F increases, the barrier width decreases and the tunneling probability for electrons rapidly increases. The transparency of such a barrier is $D = \exp\left[-\frac{4\Phi_M^{3/2}\sqrt{2m}}{3qhF}\right]$, where F the electric field, q and m are the electron charge and mass. Transparency represents the

probability of electron tunneling through the barrier. For current densities $j=1-100\text{A/cm}^2$ (amperes per square centimeter) the corresponding field would be $F > 10^7 \text{ V/cm}$.

In such strong fields, the ions, which are always present in a vacuum region in actual devices, acquire the energy over 10^3 eV in the vacuum region on the order of one micron or larger. Ions with such strong energies collide with the emitter surface leading to absorption of the ions and erosion of the emitter surface. The ion absorption and erosion typically limits the lifetime of type A emitters to a few hours of operation or even to a few minutes. Damage to cathodes in systems with the fields of similar strength has been studied in great detail and is rather dramatic.

For type B emitters (injection/avalanche type), one of the main drawbacks is that the efficiency is very small. In other words, the ratio of emitted current to the total current in the circuit is very low, usually much less than 1%. The cathode of type B based either on p-n junctions, or semiconductor-metal (S-M) junction including TiO_2 or porous Si, or the avalanche electrical breakdown need an "internal" bias, applied to p-n junction or S-M junction.

Alternatively, there have been suggestions to use the electrical breakdown processes to manufacture the cold emitters from Si. These types of avalanche emitters are based on emission of very hot electrons (with energies of the order of a few electron volts) accelerated by very strong electric field in the avalanche regime. As a result, they also have a disadvantage that the emitted current density of the hot electrons is very small.

Attempts have been made to increase the current density by depositing cesium (Cs) on semiconductor surface to use a negative electron affinity (NEA) effect. Fig. 1B illustrates the concept of NEA. As shown, a material, a p-type semiconductor in this instance, is on the left and a vacuum region is on the right. E_C represents a conduction

band of the metal. Note that the NEA effect corresponds to a situation when the bottom of the conduction band E_C lies above the vacuum level V_{ac} . One earlier p-n cathode of this type combined a silicon, or gallium arsenide avalanche region, with cesium metallic layer from where the emission took place (GaAs/Cs or GaP/Cs structures). However, Cs is a very reactive and volatile element. Thus, the GaAs and GaP emitters with Cs are not stable at high current densities.

In short, cold emitters with both high current emission and stability were not possible with previous designs.

10 SUMMARY OF THE INVENTION

In one respect, an embodiment of a cold electron emitter may include doped p-type region. The p region may be formed from semiconductors such as Si. The cold electron emitter may also include a substrate below the p region. Indeed, the p region may be formed by doping the substrate with electron poor materials.

15 Alternatively, the electron emitter may include an n+ region formed above the substrate, in which the n+ region is formed by doping the substrate with electron rich materials. The p region may then be formed by epitaxial growth of p-doped semiconductor layer on top of n+ region. The thickness of the p region is preferred to be less than the diffusion length of the electrons in the p region. When both the n+ region 220 and the p region 230 exist, the hole concentration in the p region is preferred to be less than the electron concentration in the n+ region.

The electron emitter may further include a dielectric layer formed above the p region. The thickness of the dielectric layer is preferred to be less than 2-3nm and a breakdown field of the dielectric layer is greater than the applied electric field in the dielectric layer. The emitter may still include a metallic layer formed above the dielectric 25

layer. The thickness of the metallic layer is preferred to be less than the mean free path for electron energy. The electron emitter may yet further include electrodes to n and p regions so that n+-p junction may be properly biased for operation. The electron emitter may still yet further include an M electrode, with or without the p electrode, to control the amount of current emitted from the current emitter.

In another respect, an embodiment of a method to fabricate an electron emitter may include forming a p region, for example, from doping a substrate with electron poor materials. The method may also include forming a p region on top of an n+ region, for example, by epitaxial growth of semiconductor doped with electron poor materials. The thickness of the p region is preferred to be less than the diffusion length of the electrons in the p region. Also, the hole concentration level in the p region is preferred to be less than the electron concentration of the n+ region if both n+ and p regions exist. The method may further include forming a dielectric layer above the p region and forming a metallic layer above the dielectric layer. The thickness of the metallic layer is preferred to be less than the mean free path for electron energy. The method may yet include forming n and p electrodes. The method may yet further include forming an M electrode, with or without forming the p electrode, to control the amount of current emitted from the current emitter.

The above disclosed embodiments of the present invention may be capable of achieving certain aspects. For example, the electron emitter may emit high density of electrons. Also, the lifetime of the emitter may be relatively high. Further, the emitter may be based on well-known materials (Si, SiO₂, Au etc.) and fabrication methods thereof and thus, little to no capital investment is required beyond that present in the current state-of-the-art. In addition, the detrimental effects of field emitters – cathode surface erosion, ion absorption at the emitter surface, etc. – may be avoided since the device does

not require strong electric fields resulting in stable operation. Thus stability and high current density may be combined in a single device.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Features of the present invention will become apparent to those skilled in the art from the following description with reference to the drawings, in which:

Fig. 1A is a graph of a typical energy diagram for a material surface illustrating a concept of a work function of the material;

10 Fig. 1B is a graph of an energy diagram illustrating a concept of a negative electron affinity of a material;

Figs. 2A – 2C illustrate exemplary cross sections of various embodiments of a cold emitter according to an aspect of the present invention;

Fig. 3A illustrates an exemplary energy band diagram in equilibrium across the line II-II of the embodiment of the cold emitter with p-D-M structure shown in Fig. 2A;

15 Fig. 3B illustrates an exemplary energy band diagram in equilibrium across the line II'-II' of the embodiment of the cold emitter with n+-p-D-M structure shown in Fig. 2B;

Fig. 4A illustrates an exemplary energy band diagram under bias across the line II-II of the embodiment of the cold emitter shown in Fig. 2A; and

20 Fig. 4B illustrates an exemplary energy band diagram under bias across the line II'-II' of the embodiment of the cold emitter shown in Fig. 2B.

DETAILED DESCRIPTION

25 For simplicity and illustrative purposes, the principles of the present invention are described by referring mainly to exemplary embodiments thereof. In the following

description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent however, to one of ordinary skill in the art, that the present invention may be practiced without limitation to these specific details. In other instances, well known methods and structure have not been described in detail so as not to unnecessarily obscure the present invention.

Fig. 2A illustrates an exemplary cross section of a first embodiment of a cold emitter 200 according to an aspect of the present invention. The cold emitter 200 may generally be characterized as having an p-D-M structure due to the presence of a p region 230, dielectric layer 245, and a metallic layer 240. As shown in Fig. 2A, the cold emitter 200 may include a substrate 210 and the p region 230 formed above the substrate 210. The p region 230 may be formed from a semiconductor, for which Si is the preferred material. The p region 230 may also be formed from wider band gap semiconductors. Examples of such semiconductors include Ge, GaAs, GaP, InP, and InGaP. One of ordinary skill in the arts would recognize that other materials may be used as suitable semiconductors. The hole concentration in the p region 230 is preferably on the order between $10^{16}/\text{cm}^3$ and $10^{19}/\text{cm}^3$. However, depending on the types of applications, the concentration levels may be adjusted.

Indeed the substrate 210 and the p region 230 may be formed from the same semiconductor, e.g. Si. The p region 230 may then be formed by doping the semiconductor with electron poor materials. Examples of the electron poor materials include boron. Again, one of ordinary skill in the arts would recognize that other electron poor materials may be used.

The cold emitter 200 may further include the dielectric layer 245 formed above the p region 230. The dielectric layer 245 may be formed from materials such as SiO_2 , Al_2O_3 , and the like. One of ordinary skill in the arts would recognize that other materials

may be suitable for the dielectric layer 245. It is preferred that the thickness 'a' of the dielectric layer 245 substantially meets the condition $1.5 \text{ nm} \leq a \leq 2 \text{ nm}$ (nanometer). It is also preferred that the dielectric breakdown field F_b of the dielectric layer 245 substantially meets the condition $F_b \geq (1.5-2) * 10^7 \text{ V/cm}$ (volts per centimeter), for reasons explained later.

The cold emitter 200 may still further include the metallic layer 240 formed above the dielectric layer 245. The metallic layer 240 may be formed from conductive materials. Examples of conductive materials include Au, Ag, Al, Gd, W, Pt, Ir, Pd, and alloys thereof. One of ordinary skill would recognize that other materials may be suitable as metallic layer 240, and the layer 240 may not be limited strictly to metals. Preferably, the thickness t of the metallic layer 240 is less than the mean free path l_e for electron energy. Typically, l_e ranges between 2-5 nanometers (nm). Thus, the thickness 't' should satisfy the condition $t < 2-5 \text{ nm}$.

The electron cold emitter 200 may yet include a p electrode 270 and an M electrode 290 formed above the p region 230. The p electrode 270 may be electrically connected to the p region 230 and the M electrode 290 may be electrically connected to the metallic layer 240. The p and M electrodes, 270 and 290 respectively, may be formed from conductive materials. Examples of conductive materials include Au, Ag, Al, W, Pt, etc. and alloys thereof.

In addition, the electron emitter 200 may include an insulator 250 to insulate the p and M electrodes, 270 and 290 respectively. Indeed, the dielectric layer 245 and the insulator 250 may be one and the same or may be separate.

The operation of the cold emitter 200 of Fig. 2A will be described with references to Figs. 3A and 4A. Fig. 3A illustrates an exemplary energy band diagram in equilibrium across the line II-II of the embodiment of the cold emitter 200 shown in Fig. 2A. At

equilibrium, the bottom of the conduction band energy E_C of the p region 230 lies below the vacuum level V_{ac} by the value Ψ , which is typically about 3 electron volts (eV). Because the conduction energy E_C is below that of vacuum level V_{ac} , there is no NEA.

The effective NEA may be realized by applying a finite bias voltage. When the potential on the metallic layer 240 is positive relative to the potential applied to the p region 230, the main voltage drop occurs across the dielectric layer 245 as shown in Fig. 4A. When this happens, the bottom of the conduction band energy E_C may move upward with respect to the vacuum energy level V_{ac} .

At some bias voltage, the value of E_C may become higher than the value of V_{ac} . If the thickness 'a' of the dielectric layer 245 is sufficiently small, electrons may tunnel through the dielectric layer 245 and pass through the metallic layer 240, and effective NEA may be realized. For the electrons to tunnel through the dielectric layer, the breakdown field F_b (not shown) of the dielectric layer 245 must be greater than the electric field F_O (also not shown), i.e. $F_b > F_O$, where $F_O = \Psi/a$. Thus if $\Psi \approx 3 \text{ eV}$ and 'a' substantially meets the condition $1.5 \text{ nm} \leq a \leq 2 \text{ nm}$, then the dielectric breakdown field F_b of the dielectric layer 245 should substantially meet the condition $1.5 * 10^7 \text{ V/cm} \leq F_b \leq 2 * 10^7 \text{ V/cm}$.

The electric field in the semiconductor p region 230 may be represented as $F_S = F_O (\epsilon_D/\epsilon_S)$ (not shown), wherein ϵ_D and ϵ_S represent dielectric constants of the dielectric layer 245 and the semiconductor p region 230, respectively. If the conditions stated above are met, then the field F_S exceeds the breakdown field of the semiconductor at all doping levels and avalanche breakdown occurs in the semiconductor p region 230. Electrons generated during the avalanche breakdown accumulates in a depletion region next to the dielectric layer 245 until the local quasi-Fermi level of the electrons rises above the vacuum level V_{ac} . At this point, electron emission occurs. Because very little

portion of the tunneling electrons slips into the external circuit, the efficiency of the cold emitter may be relatively high, for example greater than 10%.

Fig. 2B illustrates an exemplary cross sections of a second embodiments of a cold emitter 200-1 according to an aspect of the present invention. The cold emitter 200-1 may be described as a variation on the cold emitter 200 of Fig. 2A, and may generally be characterized as an n+-p-D-M structure due to the presence of an n+ region 220. As shown in Fig. 2B, the cold emitter 200-1 includes most of the elements of the cold emitter 200 shown in Fig. 2A, but lacks the p conductor 270 and includes an n conductor 260. For sake of simplicity, elements common to both cold emitters 200 and 200-1 will not be described in detail. It suffices to note that the behavior and the characterizations of the common elements may be similar.

The cold emitter 200-1, in addition to some of the elements of the cold emitter 200, may also include the n+ region 220 formed above the substrate 210. The n+ region 220 and p region 230 may be formed from the same semiconductor such as Si. Alternatively, the p region 230 may be formed from a wider band gap semiconductor than Si, examples of which were listed above. One of ordinary skill in the arts would recognize that other materials may be used as suitable semiconductors. The electron concentration in the n+ region 220 is preferably near or above 10^{17} - $10^{19}/\text{cm}^3$, and the electron concentration preferably exceeds the hole concentration in p region. However, depending on the types of applications, the concentration levels may be adjusted. Also, it is preferred that the electron concentration in the n+ region 220 be greater than the hole concentration of the p region 230.

Indeed the substrate 210 and the n+ region 220 may be formed from the same semiconductor. The n+ region 220 may then be formed by doping the semiconductor substrate 210 with electron rich materials. Examples of the electron rich materials

include arsenic (As), antimony (Sb), phosphorous (P), and nitrogen (N). Again, one of ordinary skill in the arts would recognize other electron rich materials may be used.

The cold emitter 200-1 may further include the n conductor 260 electrically connected to the n+ region 220.

5 Note that the p region 230, instead of being directly above the substrate 210 as shown in Fig. 2A, may be formed within the n+ region 220 as shown in Fig. 2B. The p region 230 may be formed, for example, by counter doping the n+ region 220 with electron poor materials. An example of such materials includes boron. The p region 230 may also be formed from entirely separate materials than the n+ region 220. It is
10 preferred that the n+ region 220 be formed from a wider band gap material than the p region 230.

It was noted above that the ratio of the electron concentration in the n+ region 220 to the hole concentration in the p region 230 be greater than unity. The ratio may be as much as 10 or more. Again, like the electron and hole concentration levels, the ratio may
15 be varied as well, depending on the types of application. In addition, W is preferred to be less than L, where W represents the thickness of the p region 230 and where L represents diffusion length of the non-equilibrium electrons in the p region 230, shown in Fig. 2B. The diffusion length L is typically about 0.3-1 μm .

At least one role of the n+ region 220 is explained with reference to Figs. 3B and
20 4B. Fig. 3B illustrates an exemplary energy band diagram in equilibrium of the cold emitter 200-1 of Fig. 2B along the line II' - II'. At equilibrium, a depletion layer is formed at the p-D interface between the p region 330 and the dielectric layer 245.

The operation of the cold emitter 200-1 is similar to the operation of the cold emitter 200. In this instance however, the biasing potential is such that the potential on
25 the metallic layer 240 (via the M electrode 290) is positive relative to the potential on the

n+ region 220 (via the n electrode 260). With such bias, the electrons from the electron-rich n+ region 220 are injected into the p region 230, as shown in Fig. 4B. When the thickness W of the p region 230 is less than the diffusion length L of the non-equilibrium electrons in the p region 230, the electrons may traverse the p region 230 and accumulate in the depletion layer shown in Fig. 4B until the quasi-local Fermi level rises above the vacuum level Vac. In the depletion layer, the hole concentration is very small, so that electron-hole recombination rate is very small as well. Consequently, electron emission rapidly increases, and the emitted current is much larger than the recombination current. This allows for very large currents to be emitted.

Fig. 2C illustrates an exemplary cross sections of a third embodiments of a cold emitter 200-2 according to an aspect of the present invention. The cold emitter 200-2 may also be described as a variation on the cold emitter 200 of Fig. 2A, and may also generally be characterized as an n+-p-D-M structure due to the presence of the n+ region 220. As shown in Fig. 2C, the cold emitter 200-2 includes all of the elements of the cold emitter 200 shown in Fig. 2A, and further includes an n+ region 220, an n electrode 260, and a second insulator 280 insulating the M electrode 290. For sake of simplicity, elements common to both cold emitters 200 and 200-2 will not be described in detail. It suffices to note that the behavior and the characterizations of the common elements may be similar.

The general operation of the cold emitter 200-2 is similar to the cold emitters 200 and 200-1 and thus need not be discussed in detail. However, in this instance, electron emission is initiated by forward biasing the n+-p junction, i.e. the potential on the p region 230 (via the p electrode 270) is positive relative to the n+ region 220 (via the n electrode 260). The M electrode 290 may be used to control the amount of electron emission. The emission current can be controlled by biasing the potential on metallic

layer 240 through the M electrode 290. This closes and opens the emission current from the cold emitter 200-2. This is very advantageous in applications requiring arrays with individually controlled emitters.

What has been described and illustrated herein is a preferred embodiment of the invention along with some of its variations. The terms, descriptions and figures used herein are set forth by way of illustration only and are not meant as limitations. Those skilled in the art will recognize that many variations are possible within the spirit and scope of the invention, which is intended to be defined by the following claims -- and their equivalents -- in which all terms are meant in their broadest reasonable sense unless otherwise indicated.

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